NASA TECHNICAL
MEMORANDUM

NASA TM X-1074

INFRARED ASTRONOMY REVIEW

for the Astronomy Subcommittee of the
National Aeronautics and Space Administration

by Gordon C. Augason and Hyron Spinrad

Ames Research Center

Moffett Field, Calif.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MARCH 1965

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SUMMARY

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This review describes recent research that has been done in the field of
infrared astronomy, with the main emphasis being placed on observations from
the ground. Considerable progress has been made by means of photometry in
the atmospheric windows but spectroscopy has been hindered by the generally
small amount of energy available in this spectral region and by atmospheric
interference. Before the full potential of ground based studies can be
realized, it may be necessary to find observing sites better suited to infra-
red astronomy than those used in the past. In order to choose better sites
it appears to be essential that the cause of a low frequency noise which
interferes with infrared observations be determined. It is presently
believed that this noise originates in the atmosphere. The effectiveness of
observations from balloons has not yet been demonstrated. It appears that a
vital area of infrared astronomy from the ground is sky mapping.

AUTHOR

INTRODUCTION

At the August 23-24, 1962 meeting of the NASA Astronomy Subcommittee a
sub-subcommittee was formed to review the subject of infrared astronomy. The
committee members designated were Hyron Spinrad, JPL, Gordon Augason, ARC,
and James Dozier, MSFC. Because of other commitments, James B. Dozier was
unable to participate in the writing of the review. The purpose of the review
was to determine the present state of development of infrared astronomy and
to report on this subject, in order that the Astronomy Subcommittee could
better assess possible applications of space techniques to this field. In
order to determine the information required, sub-subcommittee members con-
tacted Gerard P. Kuiper, Harold Johnson, William Sinton, Bruce Murray,
Russell Walker, Freeman Hall, Martin Harwit, John Strong, and Walter Mitchell.
All were very generous with their time and were very helpful in explaining
their present research programs as well as outlining their future plans.

Infrared observations of astronomical objects are difficult because of the generally small amounts of energy which objects radiate in this region; and, if such observations are made from the Earth, they are limited by the spectral transmission of the Earth's atmosphere. The energy restriction has been lessened somewhat by the development of relatively sensitive detectors for military applications. The increase in sensitivity of detectors, however, has been accompanied by requirements for complicated cryogenic devices and sophisticated electronic equipment. Also the detectors are often quite unstable and require a good deal of familiarization with their characteristics for the results to be useful. The limitation in transmission by the Earth's atmosphere is due mainly to the absorption of infrared radiation by H_2O, CO_2, CO, O_3, N_2O, and CH_4. Approximately 50 percent of the spectral region from 1 to 13 μ consists of windows with atmospheric transmissions greater than 50 percent. Beyond 13 μ the atmosphere is largely opaque. Much useful work can be done in these window regions. It will be the purpose of the first part of the report to describe some of the work being done and planned in these spectral regions.

Although spectral windows do exist in the atmosphere, observations in these regions are not as free from atmospheric effects as one would suppose from examining an atmospheric transmission chart. Besides minor absorption bands that exist in the windows, observers report sky noise which is detrimental to observations. Although the mechanism of this noise is not fully understood, it may be due to small masses of water vapor high in the atmosphere which radiate or absorb in the infrared. An idea of the size of these masses may be obtained from the frequency of the noise fluctuations which appear to be of the order 0.1 cps. Another source of interference with ground-based observations is that of nightglow radiation of OH. Although these bands extend from 0.6 to 6 μ, their greatest intensity is found in the region from 1.5 to 4 μ (Meinel, 1950a, b, c). F. E. Roach (1959) has stated that, "The OH bands are intrinsically so strong that, if they were concentrated in the visual region of the spectrum, they would be as bright as a prominent aurora and would constitute a permanent twilight." Between 5 and 17 μ emission by the water vapor in the Earth's atmosphere becomes a serious limitation to astronomical observation. The intensity of the radiation depends on the altitude of the observer, meteorological conditions and zenith angle of observation, but it may be many times greater than that from astronomical objects (Bell, et al., 1960). Figure 1 shows the approximate location of the windows with the regions of emission indicated.

Lunar and Planetary Laboratory (LPL),
University of Arizona

The Lunar and Planetary Laboratory at the University of Arizona has begun an extensive program to do infrared photometry and spectroscopy from the ground. The work has been done under the direction of Gerard P. Kuiper (1964) and Harold L. Johnson (1962). Most of their observations

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(approximately 80 percent) have been made at McDonald Observatory on the 82-inch telescope. The 36-inch telescope at Kitt Peak and more recently the 28-inch telescope in the Catalina Mountains have also been used. They plan to continue their studies on a 60-inch telescope when it is located on Mount Lemmon. Considerable thought by members of the laboratory has been given to the requirements of an ideal infrared observatory. An observatory which may have near ideal seeing for visible observations may be very poorly suited to infrared observations. Two aspects associated with atmospheric interference must be considered when an observing site is being chosen: (1) infrared atmospheric noise; and (2) atmospheric absorption and emission. At the present time the source of atmospheric noise is so poorly understood that a great deal of study will be required to determine the correlation between site location and noise. For instance, it is not known at this time at what elevation this noise originates. One of the most obvious ways of reducing atmospheric absorption and emission is to locate an observatory as high as possible. This will reduce the amount of absorbing substance in the atmosphere as well as reduce the width of absorption lines by reducing pressure broadening. Also to be considered are meteorological effects such as the source of the prevailing air mass in the observing locality. For instance, a site located in a normally stationary high-pressure area which is fed by cold polar air will generally be less humid than other locations.

In their pursuit of an ideal infrared observing site, members of the staff of LPL have conducted extensive site surveys in Hawaii and Arizona. Sites at Haleakala (10,000 feet) and Mauna Loa and Mauna Kea (13,000 feet) were found to provide exceptional seeing. Mt. Agassiz, which is about 15 miles north of Flagstaff, Arizona, appears in wintertime to have about 1/2 the precipital water vapor overhead as does Jungfraujoch, thus apparently making it an ideal IR observatory site.

Harold Johnson and R. I. Mitchell (1962) have worked on an infrared photometry program using a photometer of their own design. They made photometric observations in nine wavelength bands ranging from 0.35 to 5 μ. Their observations were automatically recorded on a punched paper tape along with the data necessary to reduce them. They have written complete programs for a CDC 1609 and an IBM 7090 and have reduced 3,000 observations.

In addition to the photometry done at McDonald Observatory and Kitt Peak, Johnson has done infrared photometry, beginning March 1963, at the Mexican National Observatory at Tonantzintla, Mexico. From this location, he was able to extend his observations to -50° declination. Later it is hoped that he may extend these observations to -65° by going to Chile. The present goal is to measure 1,000 of the brightest stars in nine colors.

The photometry has been done with a U, B, V, R, I, instrument and a J, K, L, M, instrument. The effective wavelength of each band as well as a few limiting magnitudes is as follows:

Detector	Band designation	Effective wavelength	Limiting magnitude 82-inch telescope
RCA 1P21	U	0.35 microns	
photo-	B	.44	
multiplier	V	.55	
ITT FW-118	R	.70	R = 18
	I	.88	
PbS	J	1.25	
	K	2.20	K = 5.5
	L	3.6	
InSb	M	5.0	

Johnson (1962) and Johnson and Mitchell (1963) have reported on observations of over 50 stars. Their results, in general, show relatively good agreement between the radiation from the stars observed and black-body radiation. Giants provide the closest agreement. From his data Johnson has computed effective stellar temperatures and bolometric corrections. His temperatures are slightly higher than those previously determined. Also it was discovered that dwarf stars have a larger bolometric correction than giants, possibly because of the excess radiation in the 1 μ region. At 5 μ it was found that (K-M) for G, K, and early M Stars is essentially independent of (B-V).

In addition to the stellar measurements Johnson and Meinel (1964) have made an infrared measurement of M-31 in the I and K bands. They found for the nucleus that the (I-K) color agrees closely with the color of K5 III and M0 III stars but that the (B-V) index did not agree with the infrared index.

In our own galaxy Johnson and J. Borgman of the Netherlands have collaborated on a study soon to be reported, in which the infrared stellar photometric measurements are used to determine the absolute interstellar absorption at various wavelengths. As reported by Borgman (1963) at Leige, they appear to have found a variation in the ratio of visual absorption to color excess from 3 (in most regions) to 7 (in the Orion Nebula). This indicates the importance of paying careful attention to the reddening parameter when the distance of reddened stars and clusters is being determined.

Johnson has made an extensive search for any gain which can be realized in the sensitivity of infrared detectors. He has experimented with detectors, filter and shield cooling, choppers, preamplifiers, and cryogenic devices. He presently has a PbS detector that is reputed to have a noise equivalent power of 10^{-14} watts. However, although he has stated that much valuable work can be done in the atmospheric windows, at the present time he feels he is only approaching the potential of his detectors within a factor of 10 to 100 because of atmospheric noise.

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Besides the photometry in the U through M spectral region, photometric measurements with the 21-inch telescope at the Catalina station and the 82-inch telescope at McDonald have been made in the 10 μ region. These measurements have been made using a gallium-doped germanium bolometer developed by Frank Low, at the Texas Instrument Corporation, before going to the Lunar and Planetary Laboratory. Besides the stars, bolometric observations have been made of Mars, Jupiter, Saturn, and the dark side of the Moon. Several stars have been observed in common with those measured by Murray and Wildey using a mercury-doped germanium detector. However, the measurements are not all in agreement. Johnson and Low have been able to attain a degree of sky cancellation of 1 part in 10^5.

Using a grating spectrometer adapted from one built by Leon Salanave, Kuiper (1962b) has obtained some of the highest resolution spectra of Venus and stars to date. The instrument, an Ebert type with a focal length of 60 cm, has two 600 line per mm gratings, blazed at 1.6 and 2.0 μ and two 300 line per mm gratings, blazed at 3.0 and 4 μ. A dry-ice cooled PbS cell is used as the detector. Runs were made at Kitt Peak with resolutions of about 700 and 250 and a run was made at McDonald with resolutions of 1500 and 800. The Kitt Peak spectra were compared with matching solar runs and the McDonald spectra with lunar spectra. From the Venus curves an abundance of 2 km-atm of CO_2 was determined for the phase of the observations. The abundance ratios of C^{13}/C^{12} and O^{18}/O^{16} were established as being the same as that for the Earth to an accuracy of ±20 percent. Although a temperature determination has not been completed for the CO_2 hot bands, the spectra clearly indicate a temperature hotter than the 300° K bands of the laboratory spectra. Also an upper limit of CO was placed at 10 cm-atm. The stellar spectra obtained by Kuiper are of the same high quality as his planetary material. Most of this work is to be reported at a later date. However, two unknown bands were found on Alpha Orionis at 1.6 and 2.7 μ which have tentatively been identified by A. Meinel as the ground state rotation-vibration bands of CO (Kuiper, 1962b). Also, low resolution spectroscopic observations of Omicron Ceti exhibit strong broad absorption bands located in the 1.4 and 1.86 μ terrestrial water vapor regions. These bands have been attributed to "hot" water vapor (Kuiper, 1963).

A new spectrometer is being constructed for use on the 84-inch telescope which should be able to resolve the rotational lines in stellar and planetary bands. The design goal for this instrument has been a resolution of 10,000 at 2 μ.

Concurrent with the astronomical observations laboratory studies have been carried on with a 2-meter multiple reflection-absorption cell on loan from the Canadian Research Council (path lengths up to 80 meters). More recently a 22-meter cell (path lengths up to 4 km and pressures of 8 atmospheres) has been installed in the new Lunar and Planetary Laboratory. Under the direction of A. Meinel a program has been undertaken to study flame and arc spectra of oxides and hydrides. The purpose of this program is to help identify many of the features observed in stellar spectra.

The Lunar and Planetary Laboratories have also begun an infrared balloon program. On a successful flight to 85,000 feet in October 1963 the infrared absorption characteristics of the Earth's atmosphere were checked. Later flights are planned for the purpose of making astronomical observations.

<center>Institut d'Astrophysique (Belgium) and
National Physics Laboratory (England)</center>

Gebbie (England), Delbouiller (Belgium), and Roland (Belgium) have been the main proponents of the use of interferometric techniques to obtain astronomical spectra. Although Michelson (1927) was the first to recognize that one could obtain spectra by the use of an interferometer, it was not until Felgett (1954) pointed out the advantages of an interferometer spectrometer for the suppression of detector noise that investigators realized the potential of such an instrument. Felgett pointed out that if a detector is not background limited one could expect an increase in the sensitivity of an interferometer spectrometer over a conventional spectrometer by a factor of $\sqrt{N}$ where N is the number of spectral elements resolved by either spectrometer. This advantage is referred to as Felgett's advantage. (For detectors which are background limited, Felgett's advantage does not exist.) Another advantage that an interferometer spectrometer has over a slit type spectrometer is a larger acceptance cone so that it often can accept all the radiation incident upon it from an extended source. In practice an interferogram obtained from the interferometer is converted to a spectrogram by means of a Fourier transformation. This transformation may be performed with an analog spectrum analyzer. When high resolution is required, the transformation is made by a digital computer. It appears that in the laboratory the gains expected for an interferometer spectrometer have been realized (Gebbie, et al., 1961, Lowenstein, 1960). However, the use of an interferometer for astronomical applications has not been entirely successful. Gebbie, et al., have been the first to obtain any quantity of astronomical data. Gebbie, et al., (1962) used a cooled PbS cell to obtain a spectrum of Venus out to 3 μ. The spectra obtained do not have the resolution expected and they have several extraneous absorption lines. During the summer of 1962, Gebbie, et al., obtained more spectra of Venus at Lick Observatory with the 120-inch reflector but these have not been published.

The failure of interferometry to live up to its expectation in astronomy appears to be due partially to the complexity of building an adequate interferometer and partially to the interpretation of how extraneous data effects in an interferogram are transformed when a spectrum is reconstructed. In constructing an interferometer of the Michelson type, it has proved very difficult to develop a linear drive for the mirror and to keep the light beams parallel during the mirror's displacement. One approach to the linearity problem is to monitor a monochromatic light source interferometrically while making an interferogram in order to obtain an error signal. Corner cubes have also been used to make the two interfering beams parallel. Some of the things that affect a spectrum are (1) noninfinite scans, (2) the

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varying wavelength response and lack of intensity linearity of detectors, (3) source and system noise, (4) loss of signal as a result of poor pointing, insufficient sampling, or fluctuations in the absorbing media between the source and the instrument. All of these items affect the wavelength and intensity of a spectrum transformed from an interferogram. Sky noises caused by moist air masses probably have the most disturbing effect on spectra. It is for this reason that the use of interferometers for astronomical spectroscopy may be limited to use outside the Earth's atmosphere.

Lowell Observatory

Sinton (1963) is one of the earliest investigators in modern infrared astronomy. He obtained medium resolution spectra of Venus and Mars using the 200-inch reflector at Mount Palomar around 1954. He used an Ebert grating type monochromator with a resolution of 125 and a Golay cell detector. The observations were made in the 8-14 μ region. More recently Sinton (1962) has obtained spectra (resolution less than 200) of the planets and stars using a LiF, Littrow-mounted prism spectrometer on the Lowell 42-inch reflector with a cooled, 77° K, lead sulphide cell. The noise equivalent power achieved at 3.75 μ was 10^{-12} watts. The spectra of Venus revealed the presence of both CO and CO_2 in the planet's atmosphere.

As mentioned before, one of the drawbacks to spectroscopy performed with an interferometer is that sky noise affects the entire transformed spectra. In the conventional case, the noise affects only a localized portion of the spectra and its effect can be identified. However, in the case of a transformed spectra, any fluctuation in the optical path between the source and the instrument affects the wavelength and intensity representation of the entire spectra. In order to detect this sky noise and to use the error signal derived from it to compensate for the error, Dr. Sinton is constructing an ingenious polarizing interferometer which is very similar to a single element Lyott filter. It consists of a polarizer, two stacked crystal wedges, one fixed and the other movable, a rutile bias plate and a rutile Wollaston prism. Rutile is used throughout the instrument because of its high birefringence and its good transmission properties. The ordinary ray and extraordinary ray of a beam of light which is incident on the instrument go to two separate detectors. A scan is performed by slowly translating the movable crystal wedge to change the retardation of the light passing through the polarizer. Consequently, varying interference patterns appear at each detector. An instrument such as described is very sensitive to a change in phase of the incoming light. A ratio may be taken of the difference divided by the sum of the intensity of the ordinary ray and the extraordinary ray. If some change occurs in the optical path between the source and the instrument, this ratio will change. The interferometric data are handled in the same manner as the data from conventional interferometers. This type of instrument should be very useful for obtaining spectroscopic information from weak astronomical sources. It should provide Felgett's advantage and the aperture advantage, and it should be able to discern and make appropriate corrections for seeing fluctuations. Also, it should be less sensitive

to temperature fluctuations and will not have most of the mechanical problems of a Michelson type instrument. Presently the instrument is in the final stages of construction and adjustment.

California Institute of Technology

The only astronomical observations made in the 8-14 μ window until recently were those previously mentioned by Sinton. This spectral region is particularly interesting to planetologists because it is here that emission spectra from the various planets may be expected. Unfortunately, this is also the region of strongest emission by the Earth's atmosphere. The emission from the Earth's atmosphere may be many times greater than that from astronomical objects. Also, the telescope and photometer components within the field of view are intense sources of radiation. Bruce Murray and his associates have constructed a dual-beam infrared telescope photometer which incorporated the latest technology to obtain measurements of the Moon, planets, and several stars in this spectral region.

To reduce the emission from the telescope, the reflecting elements were gold coated. Then the field of view of the detector was defined by apertures along with a field lens attached to the detector heat sink. The detector, photoconductive mercury-doped germanium, was cooled with liquid hydrogen. The spectral bandpass of the photometer was set by the response curve of the detector on the long wavelength end and by an interference filter on the short wavelength side. The description of the instrumentation is given by Westphal, et al. (1963).

The background radiation is balanced out by alternately looking at background plus object and background minus object and then processing the signals by means of a special autocorrelation and synchronous rectification network. With this arrangement a noise equivalent power of 2×10^{-12} watts was achieved. This allowed a minimum detectable temperature of about 105° K to be measured under good conditions.

The equipment described was installed in an observatory at 12,800 feet on White Mountain near Big Pine, California, to reduce the effects of atmospheric moisture. Observations of Jupiter were obtained with a signal-to-noise ratio of 10 (Murray and Wildey, 1963a). The mean temperature was 128° K with a standard deviation of 2.3° K. No signals were obtained for Saturn, therefore, it was assumed that its temperature is less than 105° K.

At White Mountain, Murray and Wildey (1963b) scanned the Moon in right ascension coincident with the lunar equator. They measured temperatures of 141° K, 133° K, 121° K, and 111° K after approximately 6, 12, 24, and 48 hours, respectively, of lunar nighttime. In addition to determining the cooling curve, they discovered "hot spots" while they were scanning the surface. They attributed the "hot spots" to surface regions of high thermal conductivity. They also detected Alpha Orionis with the photometer. This was the first time such an object had been detected outside of the solar system in the 8-14 μ

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region. The flux measured for Alpha Orionis was about 2/5 that expected from previous calculations based on measurements at shorter wavelengths.

Bruce Murray and others have made some measurements at Mount Wilson and Palomar with conventional aluminum-coated mirrors and have not found the results to be too different from those obtained with gold mirrors at White Mountain. This indicates that height is not the only consideration in choosing a site for an infrared observatory. Using the 200-inch telescope at Palomar with a liquid-hydrogen cooled, mercury-doped germanium photometer, Murray and Wildey (1963c, d) and Wildey and Murray (1963a, b) have obtained measurements on 25 stars, Venus, the satellites of Jupiter and the Moon in the 8-14 μ region. The earliest stars measured were Beta Orionis B8 Ia and the latest star was X Cygni M7e. The large Jovian satellites, Ganymede and Callisto, appeared to be hotter than JI and JII. Scans across Venus with high spatial resolution showed asymmetrical limb darkening. The same type scans across Jupiter have not shown temperature variations (Murray and Wildey, 1964).

Robert Leighton, Guido Munch, and Gerry Neugebauer are building an f/1 60-inch telescope to use at Mount Wilson for sky surveys. The method to be used will be similar to that originated by Freeman Hall of I. T. T. which is described later. They will use a broadband-pass filter which will include all of the 1.89 μ atmospheric window. The field of view will be approximately 1-3 minutes of arc with an accuracy in scan of ±1 minute in right ascension and ±10 minutes in declination. The scan is planned to be semiautomatic.

International Telephone and Telegraph Corporation (Federal Laboratories)

Freeman Hall (1961, 1963) has used a radiometer originally developed to measure infrared radiation emitted and reflected from a satellite to determine the PbS magnitude of a group of stars and to perform a sky survey (Hall and Stanley, 1962). The instrument consisted of a dry-ice cooled PbS cell photometer attached to a 20-inch aperture Newtonian telescope. The field aperture was $1/4° \times 1/4°$, with a copper reticle giving space filtering of 1167 waves per radian.

Hall, et al., (1960) used this instrument to measure the PbS magnitudes and PbS irradiance of 40 stars and 4 planets. The results were then compared with those obtained by Felgett (1951) and Pettit and Nicholson (1922) and calculated by Larmore (1956).

Hall's measurements agreed quite well with those made by Felgett using lead sulphide. Exact agreement was not expected because of the differences in the temperature of the detectors used in the two programs and because of the internal inconsistencies in Felgett's measurements. Hall's results for the hotter stars were generally in accord with the measurements made by Pettit and Nicholson using a bolometer; but the lead sulphide results usually indicated greater energy for the class K and M stars. The lack of

agreement for cooler stars may possibly be accounted for by the increase in transmission (around 2 μ) of the carbon black that Pettit and Nicholson used to blacken their bolometer.

The irradiance values for the stars measured by Hall are 1.4 times greater for the hotter stars and 2 to 4 times greater for the cooler stars than the values predicted by Larmore. The PbS color index observed was compared with the color index expected for a black body. The agreement was good except for the stars M0 or later, where the PbS index was greater than expected. Most of these stars were variables.

From the stellar irradiance measurements it was determined that stars in the -2 to 1 magnitude region produce an integrated sky brightness of 1×10^{-15} watts/cm^2-deg^2-μ, while the stars in the 1 to 3 magnitude region produce 3×10^{-15} watts/cm^2-deg^2-μ.

The internal consistency during a night's observation was 0.07 magnitude with night to night variation never greater than 0.12 magnitude. The PbS cell noise-limited flux density was determined to be 9.0×10^{-15} watts/cm^2 at the detector peak. Even with the high degree of space filtering employed, a randomly varying irradiance of 2×10^{-2} watts/cm from the atmosphere in the 2-6 μ region made it difficult to reach cell noise limited operation.

The same instrument used to make the stellar irradiance measurements has been used more recently to perform a sky scan. The scan was performed by allowing the stars to drift in right ascension and a declination scan was performed by nodding the Newtonian Mirror in the telescope. After a 2.5° strip of the sky had been scanned the telescope was reoriented in declination and another strip was scanned.

Each area of the sky was scanned several times and sources detected were described in terms of the probability that an actual detection was made. Strong sources had a 100 percent probability of detection; the definite sources, 90 percent; the probable, 60 to 70 percent; and the possible, 20 to 30 percent. Eighteen percent of the sky was surveyed. One surprising result of the survey was that many extended sources appear to have been discovered but have not been identified. Also, 34 percent of the probable point sources detected did not correspond to stars in the Becvar Catalog or the Boss General Catalog. Eastman Kodak and Ohio State University (EK/ARD EO-735, 1961) performed a survey in which they predicted the infrared magnitude of stars, near infrared 0.0 magnitude or brighter, on the basis of black-body extrapolation. Of the 46 stars common to the two surveys, 19 were not detected by Hall. However, 21 stars were detected, corresponding to a strong or definite detection, which were not on the EK-OSU list. This indicates the danger of attempting to predict infrared magnitudes. Some of the detected but not predicted sources may possibly be accounted for as near stars with cool companions. Several interesting stars were discovered. Both K Ser and ST Herc showed large intensity fluctuations, indicating the possibility of infrared variable stars.

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A new solid aluminum telescope with a polished aluminum 24-inch f/2 primary is nearing completion. This will be a 30-element multiple-channel device. A noise equivalent power density of 10^{-16} watts/cm^2 is anticipated in the 1-3 μ region. The 30 detector elements will cover $1/2^0$ in declination with a resolution of 1 minute of arc. It is hoped that space filtering will not be necessary. When the telescope is finished, a sky mapping program similar to that performed in the past will be attempted.

Ohio State University and Eastman Kodak

Eastman Kodak, with the Ohio State University as a subcontractor, contracted with the Army to make a sky survey to measure the radiance of a number of stars to check their agreement with a black-body model. The Ohio State University work was largely under the direction of Walter E. Mitchell, Jr., while William H. Haynie provided the leadership for Eastman Kodak. A three-channel infrared photometer was developed by Kodak which responded in the following bands (EK/ARD ED-692, 1962).

Band	Wavelength	Detector
X	2.0 to 2.4 μ	N-Type PbS (uncooled)
Y	3.2 to 4.2 μ	P-Type (Plumbide) (cooled to liquid N_2 temperature)
Z	7.5 to 13 μ (flat response)	Copper-doped germanium (cooled to liquid Ne temperature)

The bandpass is determined by interference filters and detector response. The Z band is split by the ozone absorption band. The photometer chopper is constructed so that the detectors look alternately at the sky and then the star, at a rate of 480 cps. The output is synchronously rectified and integrated for times up to 5 minutes. The photometer with the 69-inch Perkin telescope was theoretically capable of detecting an irradiance of 7×10^{-19} watts/cm^2 in the 3 to 4 μ band.

Approximately 70 stars were observed in the X and Y bands and the Sun, Moon, Mars, and Venus were observed in the Z band. The data were reduced in terms of magnitudes. Color indices were then established for each star as follows: X.I. = m_V-m_X and Y.I. = m_V-m_Y where m_V, m_X, and m_Y are the respective magnitudes in the visible X and Y bands. Plots were formed of color index versus temperature. In both the X band and Y band the stars agreed well with the black-body curve except at the lower stellar temperatures where the index was greater than that expected for a black body. The difference in index occurs for nonvariable as well as variable stars although it is greater for the variable stars. This discrepancy in PbS and black-body color indices for low temperature stars was also noted by Hall as mentioned previously. Another discrepancy observed was that super giants at all

temperatures always show a greater color index than the calculated black-body indices. This seems to indicate that the super giants are emitting an excess of radiation in the spectral bands measured.

Three abnormal stars were discovered: T Coronae Borealis, X Aquarii, and E Aurigae. T CrB should have been 6 magnitudes above the limit of the instrument, but it was unobservable. This star, also known as a blaze star, had other characteristics that distinguished it from the conventional long period variable. X Aquarii was over 2 magnitudes fainter than calculated in both PbS bands. The observations of E Aurigae gave indications that its companion star, an infrared star, temperature 1350° K, was detected. This raises the question of how many other stars of this type are located in our universe. Phillip Barnhart (1962) calculated the possibility of discovering a protostar in the infrared and came to the conclusion that it may be possible to observe an individual pre-Hertzprung-Russel diagram protostar in a nearby young cluster with a large telescope. Walter E. Mitchell (1961) has discussed protostars and other topics of interest to infrared astronomy in a paper presented at an informal infrared astronomy symposium at Johns Hopkins University.

Recently the 69-inch Perkins reflector was moved to Lowell Observatory at Flagstaff, Arizona. This telescope is being instrumented for a three-channel I. R. photometry program similar to that conducted in the past. The Perkins reflector will be used to supplement work being conducted on the 32-inch Delaware reflector.

Air Force Cambridge Research Center

Russell Walker (1962a) has begun an extremely interesting program in infrared astronomy. This program was originally undertaken to determine the celestial background for military purposes. Since, according to their calculations, 85 percent of the total radiation in any direction in the galaxy comes from type K and M stars, the infrared spectral region is very important. Walker (1962b) has compiled a table of black-body functions particularly useful to astronomers attempting to determine the total radiation from a star. In addition, he has written an article on methods of converting various photometric measurement to radiometric quantities. Using these conversion techniques Walker has determined the total radiation curves of 70 stars. These are all of the stars that have been measured photoelectrically in at least 6 wavelength regions. The energy curves have been compiled and will soon be published. Also he has computed a sky map showing how the sky will look at 2 μ.

Walker has also obtained some total energy curves of planets and stars using an interferometer. He is presently constructing a PbS nitrogen cooled photometer which will be used to map the sky at 2.2 μ. The instrument will have a bandpass of 0.1 μ. A meridional scan will be made by alining a $2^O \times 1/4^O$ field stop along the meridian. Only one detector will be used and spatial position will be determined by means of frequency and phase information (associated with radiation from the stars) as imparted by a multiple

segmented reticle chopper. Simultaneous extinction measurements will be made using a separate telescope with a seven-channel photometer. (U, B, and V channels along with four infrared channels will be provided.)

Russian Infrared Astronomy

U. I. Moroz (1962) has obtained spectra of Venus, Jupiter, and Saturn from 0.9 to 2.5 μ using the 50-inch telescope at Crimea. He used a lead sulphide detector with resolutions ranging from $\Delta\lambda 0.002$ μ on Venus to $\Delta\lambda 0.02$ μ on Saturn.

For Saturn he concludes the rings are covered with frost or that the particles consist of ice, which is in agreement with Kuiper. Also, his spectra of Jupiter agree well with Kuiper's, but for Saturn he finds the NH_3 abundance less than 20 cm-atms.

Moroz's Venus observations led him to conclude that the infrared spectrum does not show depressions expected from ice crystal reflections. This again agrees with Kuiper, but not with Sinton.

Moroz (1960, 1961) has also scanned the galactic center and the crab nebulae in the PbS spectral region and made isophote maps.

BALLOON ASTRONOMY

Many advantages can be realized by doing infrared astronomy from a balloon. The most obvious advantage, of course, is the reduction of atmospheric absorption. Also, image diffusion and fluctuation due to atmospheric turbulence is eliminated. This makes it possible, in principle, for a telescope to realize its theoretical optical resolution. This should permit improved spatial resolution, and the reduced image size should result in an improved signal-to-noise ratio.

Early balloon astronomical flights depended upon an observer to guide the instruments; however, it was soon found that the observer's movements were detrimental to the pointing process and that his weight could better be replaced by guidance and control instrumentation. The most advanced balloon system at the present time weighs 6,000 pounds, and has a ceiling of 80,000 feet. It is doubtful that balloons of this weight will soon exceed this altitude.

At balloon altitude one is above most of the water vapor which has been frozen out. However, the balloon depends upon an atmosphere for its support and there are other constituents at this altitude. Ozone is above the balloon which precludes observations in the ultraviolet and at 4.7, 9.6, and from 13 to 15 μ. CO_2, CO, and N_2O are still present at balloon altitude, although their absorption bandwidths are considerably reduced by the

reduction in pressure. When balloons reach altitude they are usually so distended that observations are restricted to the angle between the horizon and within 30° of the zenith. Thus, some of the advantages gained at balloon altitude may be reduced by making observations through long-slant paths. In addition to the absorption at balloon altitude, one may expect the OH emission that is observed as nightglow from the ground.

Johns Hopkins University

John Strong (1961a, 1962) was one of the first persons to use balloons for infrared astronomy. His first flight, which was supported by ONR-NSF, occurred November 1959. The purpose of the flight was to measure the water vapor content of the Venus atmosphere. The flight had been preceded by careful planning for a Mars flight the previous year which was not flown because of the rupture of the balloon. The instrumentation consisted of a 16-inch Schmidt telescope, 12-inch effective diameter, mounted on top of the Navy Strato-Lab with a Czerny-Turner spectrometer. The detector used was PbS with 14 exit slits at the positions of the water vapor lines in the 1.13 μ water band. Multiple slits provided an increase in flux and sensitivity.* The particular slit arrangement was suggested by William S. Benedict.

In the 1959 flight, no conclusive evidence was derived as to the amount of water vapor on Venus. This has been blamed (a) on the difficulty of making observations because of the swaying of the gondola, (b) on the fact that the Moon was not available for monitoring residual water vapor in the Earth's atmosphere, and (c) on the lack of information concerning the Venus atmospheric pressure needed to interpret the data obtained.

The Johns Hopkins University Laboratory of Astrophysics and Physical Meteorology has a continuing program of high altitude infrared astrophysics. Their telescope is now equipped with automatic acquisition. This equipment was flown on May 4, 1963 with a mylar scrim balloon but the mission aborted, as the result of a faulty high-voltage connection. On a second attempt on May 10, the balloon (polyethylene) failed at the tropopause. The equipment has been improved and is being readied for another try, on the Venus water observations, in the Spring of 1964. Coarse guidance is provided by a solar sensor, since daytime flights in the infrared are practical. Two identical gondolas, each with a telescope and spectrometer, will be provided.

The high-altitude astronomy program of Johns Hopkins has been outlined by Strong (1961b). Other spectroscopic investigations are planned, including high resolution spectra of the Sun, and low resolution emission spectra of Mars and Venus in the infrared out to $\lambda > 40 \mu$. In later flights multiple slits as used for Venus will be used for the detection of water vapor on Mars.

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*Currently JHU is using 23 slits in the 1.13 μ band. Later they plan to work with other bands, farther in the infrared, using helium-cooled photoconduction detectors.

University of California (Space Science Laboratory)

Harold Weaver received a contract from NASA to instrument Stratoscope II with an infrared spectrometer to obtain spectroscopic data from Mars during the 1963 opposition.

Project Stratoscope is under the direction of Martin Schwarzschild (1962) at Princeton University. It is sponsored by NSF, ONR, and NASA. Stratoscope was conceived as a project to obtain high resolution astronomical photographs. Perkin-Elmer built the system for both Stratoscope I and II. The Stratoscope II system consists of a telescope with a 400 pound, 36-inch primary mirror capable of photographic resolution of 0.1 second of arc, and a 40-channel command and a 64-channel telemetry system which is designed to provide a remote control guidance tracking system with an accuracy of 0.02 seconds of arc. Stratoscope II uses a 5,250,000 cubic foot balloon to carry the 6,000 pound payload to an altitude of 80,000 feet.

A spectroscopic flight was flown March 1, 1963. The photographic optical configuration was modified to direct infrared radiation to a Wadsworth-mounted fluorite prism spectrometer. The detector used was a newly developed gallium-doped germanium bolometer (Low, 1961). It required a Dewar filled with liquid helium and it operated at a temperature of 1.5° K. The noise equivalent power achieved at balloon altitude was around 10^{-13} watts. The spectral region covered was from 1 to 7 μ with a resolution of 0.02 μ at 3 μ. Several difficulties were encountered during the first flight. Television cameras used for guidance were inoperative during much of the flight. Interference with the transmitted spectral data was caused by the command telemetering system. It had been planned to monitor the Moon and certain stars but the instrument could not be made to track the Moon. Mars was observed for 16 minutes. Data from the flight indicated that water vapor in the martian atmosphere was less than 0.004 and probably less than 0.001 that of the Earth's atmosphere.

Donald Rea (1963) and Rea and Welch (1964) at the Space Science Laboratory have written two comprehensive review articles on planetary, molecular spectroscopy, and emission and reflection from planetary surfaces which deal largely with the infrared spectral region.

Princeton University

A Stratoscope II balloon flight to perform infrared spectroscopy of stars and planets was flown November 26, 1963. This flight was entirely under the direction of Martin Schwarzschild (1964). Seven red giants were observed, Aldebaran, Betelgeuse, Mira, Mu Cephei, Mu Geminorum, R Leonis, and Rho Persei. Strong absorption bands were observed on Jupiter and the stars. The amount of residual water vapor in the atmosphere was monitored by observations of Sirius and the Moon.

CONCLUDING REMARKS

This review has indicated that useful but restricted infrared astronomy may be done from the ground. However, before the potential of ground-based infrared astronomy can be realized, research is required to determine the location requirements of an ideal observing site. At the present time it is hard to define these requirements because the source of sky noise is not known. Infrared astronomy has been attempted from balloons, but because of flight restriction and complexities their effectiveness to date has not been completely determined.

The area of greatest progress in the infrared has been photometry in the atmospheric windows. By means of photometry the temperature, color index, bolometric corrections, and the variability of several classes of stars have been studied. Because of the greater complexity of instrumentation required, spectroscopy has not advanced as fast. However, it has been shown that under certain conditions relatively high resolution stellar spectra can be obtained.

Ames Research Center
    National Aeronautics and Space Administration
        Moffett Field, Calif., April 20, 1964

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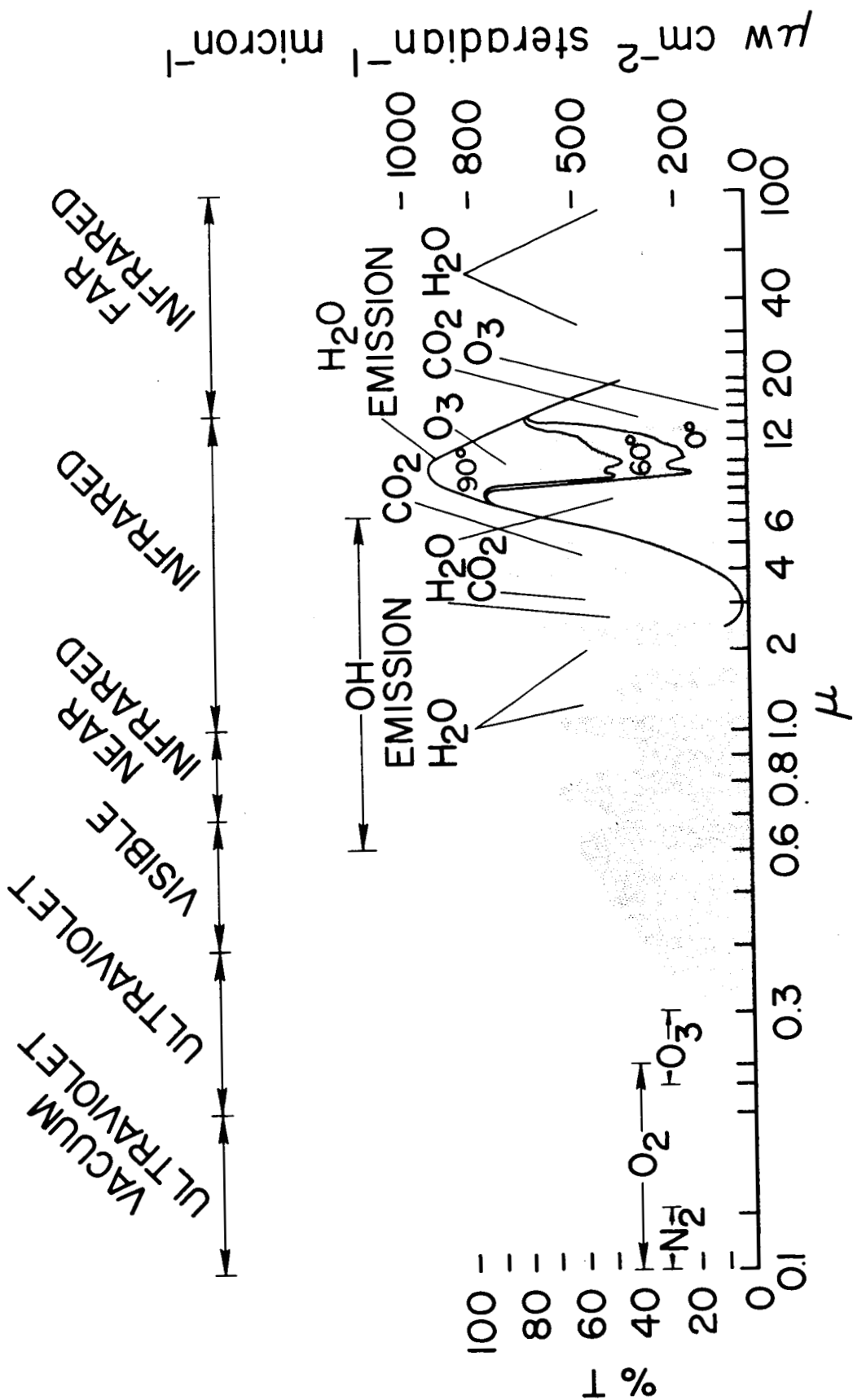
Fig. 1.- Transmission of Earth's atmosphere at sea level.